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"Plasma Properties and Magnetic Field Structure of the Solar Corona, Based on Coordinated Max '91 Observations from SERTS, the VLA, and Magnetographs"

covering the period 12 July 1994 — 12 January 1995

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(NASA-CR-197864) PLASMA PROPERTIES AND MAGNETIC FIELD STRUCTURE OF THE SOLAR CORONA, BASED ON COORDINATED MAX 1991 OBSERVATIONS FROM SERTS, THE VLA, AND MAGNETOGRAPHS Semiannual Report, 12 Jul. 1994 - 12 Jan. 1995 (Hughes STX) 12 p

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1 Introduction

The purposes of this investigation are to determine the plasma properties and magnetic field structure of the solar corona using coordinated observations obtained with NASA/GSFC's Solar EUV Rocket Telescope and Spectrograph (SERTS), the Very Large Array (VLA), and magnetographs. The observations were obtained under the auspices of NASA's Max '91 program.

The methods of achieving the stated purposes of this investigation are:

- to use SERTS spectra and spectroheliograms to determine coronal plasma properties such as temperature, density, and emission measure
- to use the coronal plasma properties to calculate the intensity of the thermal bremsstrahlung microwave emission from the coronal plasma (the minimum microwave intensity expected from the emitting plasma)
- to establish which emission mechanism(s) contribute to the observed microwave emission by comparing the calculated thermal bremsstrahlung intensity with the observed microwave intensity
- to derive the coronal magnetic field for regions in which gyroemission contributes to the microwave emission by determining the appropriate harmonic of the local electron gyrofrequency
- to derive the coronal magnetic field for regions in which thermal bremsstrahlung emission alone is responsible for the observed microwave emission by calculating the magnetic field which yields the observed microwave polarization
- to derive three-dimensional models of the coronal plasma and magnetic field which are consistent with all of the EUV spectra and spectroheliograms, as well as with the intensity and polarization maps at all of the microwave observing frequencies
- to compare the coronal magnetic field derived from the coordinated multiwaveband observations with extrapolations from photospheric magnetograms.

When the proposal requesting NASA support for the research briefly outlined above was submitted back in September of 1993, the quality of the data from the SERTS flight of 17 August 1993 was not yet known. The proposal stated, however, that if those data became available and were of sufficiently high quality, they would be analyzed in addition to the data from the 1991 flight. I have examined the data from the 1993 flight and found them to be of superior quality even to the data from the 1991 flight. I therefore decided to analyze those data simultaneously with the 1991 data.

2 Achievements

During the first six months of performance under this grant, I concentrated heavily on the reduction and analysis of SERTS spectral data. I analyzed data from both the 7 May

1991 and the 17 August 1993 flights simultaneously. For each flight, digitized, calibrated spectral arrays were provided by Drs. Joseph Davila and Roger Thomas of the Laboratory for Astronomy and Solar Physics at NASA/GSFC. For each flight, film was exposed at four different durations (each referred to as a "frame" in SERTS parlance) in each of two different pointing positions. The use of different exposure durations effectively increases the dynamic range of the film: the longest durations yield a large number of well-exposed spectral lines and a small number of overexposed lines, while the shorter durations provide well-exposed versions of the lines which are overexposed in the longer exposures.

I began my spectral analysis by carefully removing plate flaws from the longest exposure for each pointing position for each flight. I ascertained which lines in these frames were overexposed (*i.e.*, which lines had relative intensity values which fell outside the linear portion of the film's D log E relation) and removed plate flaws (if necessary) from the next longest exposure only in the vicinity of the lines which were overexposed in the longest exposures. In this way I obtained the maximum number of well-exposed emission lines. I then determined which portions of the slit spectra were associated with particular solar features (*e.g.*, quiet sun, active sun, and areas above the limb). This was done by both visual inspection of spatially resolved slit spectra, and by comparison with coordinated ground-based observations. A characteristic spectrum was then obtained for each feature by averaging over the individual appropriate pixels. This substantially reduced the noise, and provided high-quality spectra characteristic of various solar features for further detailed analysis. For the 1991 flight I obtained characteristic spectra for quiet sun areas, areas along the edge of AR 6615, and areas above the limb. For the 1993 flight I obtained spectra for quiet sun areas and for AR 7563.

A number of IDL programs were written, applied, and revised as needed in order to extract useful information from the five characteristic spectra. Such information includes, for example, the wavelengths, integrated intensities, widths, and corresponding uncertainties associated with observed emission lines. One program was written to facilitate the extraction of emission line candidate features. Features were accepted as being line candidates if their peaks rose above three times the local background noise (sigma). Another program was written to remove line candidate features from the characteristic spectrum, and so calculate the characteristic background for each spectrum. A different program was written to fit gaussian profiles to specified line candidate features. This program calculates the centroid of the fitted gaussian (which yields an accurate determination of the line wavelength), the amplitude above the background and the width (which yield the total line intensity), and the corresponding uncertainties. The standard IDL gaussian fitting routine fits the specified data with a gaussian plus a quadratic background, *i.e.*, it determines six fitting parameters. I found that noise in the local background could cause this fitting routine to obtain erroneously large or small line amplitudes, depending upon the concavity of the quadratic. I revised the relevant IDL routines to accommodate two additional cases: a gaussian plus a linear background (five fitting parameters), and a gaussian with zero background (three fitting parameters). After some experimentation, I decided that fitting the gaussian with zero background was the best alternative, since this case is not sensitive to noise in the local background, and it assumes that the background that was determined by line candidate feature subtraction is accurate.

Once the project was underway, it came to my attention that Dr. Brunella Monsignori Fossi had recently revised her iron line emissivity calculations for all of the stages of ionization of iron which I found in the SERTS 1991 and 1993 flight data. She has compared her calculations with those recently published by Brickhouse, Raymond, & Smith (1995, to appear in ApJS) and found excellent agreement. Dr. Monsignori Fossi has also very recently completed similar calculations for other elements, including silicon. Since she was interested in using real spectra to test her differential emission measure code, and I was interested in using the most up-to-date emissivity calculations available in order to test the SERTS calibration and perform density and temperature diagnostics, we decided to collaborate.

Included in this document are two lists of EUV line intensity ratios (tables 1 and 2). The first is based upon the 1993 active region (AR 7563) characteristic spectrum, and the second upon the 1993 quiet sun characteristic spectrum. Similar lists exist for the three characteristic spectra obtained from the 1991 flight data. For the sake of brevity I present only the results from the 1993 flight in this document. The first column in each list gives the wavelength of the emission line whose intensity is in the numerator, and the second column gives the wavelength of the emission line whose intensity is in the denominator. The third column gives the measured numerical value of the intensity ratio, and the fourth column gives its uncertainty. The fifth and final column gives one of three quantities. If the corresponding theoretical line intensity ratio is density and temperature insensitive, then this column indicates this constant value with the expression "constant=x.xxx". (If the ratio is weakly sensitive to density and/or temperature, the expression in this column is written "constant$\sim$x.xxx".) If the line intensity ratio is density sensitive, the corresponding log of the density value is provided, along with its associated error bars. If the line intensity ratio is temperature sensitive, the corresponding log of the temperature is provided, along with its associated error bars. (I list here only temperature-sensitive iron line ratios which are relatively insensitive to density; additional, density-sensitive line ratios can of course also be used as temperature diagnostics.) All of the values listed in the fifth column were obtained from line emissivity calculations provided by Dr. Monsignori Fossi.

3 Analysis

Several conclusions can be drawn from the line intensity ratios listed in tables 1 and 2. First, the agreement between the measured and the theoretical values of the density- and temperature-insensitive ratios confirms the validity of the SERTS relative wavelength calibration. Second, the wide scatter in the calculated density values, particularly as obtained from among various ratios of Fe XIII lines, is disturbing. Similar such scatter has been attributed by Doschek (1984, ApJ **279**, 446) and by Brickhouse, Raymond, & Smith (1995, to appear in ApJS) to the presence of multiple density structures along the line of sight. Preliminary attempts to derive appropriate multiple densities and their corresponding volume filling factors for the SERTS data have not been successful. The extremely low density derived from the ratio of two of the strongest Fe XIII lines (320.81 and 359.67 Å) is especially troubling; perhaps it can be attributed to uncertainties in the atomic physics parameters. Third, taken together, the density sensitive line intensity ratios indicate that structures of similar density are found in both active and quiet sun regions. Fourth, the line ratios which are sensitive to higher temperatures indicate that the active region is hotter than the quiet sun (not surprising). This is further supported by the presence of Fe XVII emission in the active region spectrum, and the absence of Fe XVII emission in the quiet sun spectrum (despite the longer exposure time and the larger number of pixels over which to average for the quiet sun spectrum).

The SERTS observations point to a very complex picture of the solar corona, suggesting the presence of multiple density structures embedded in multithermal plasma. In order to achieve the goals of this work, it appears that the best approach is to use a differential emission measure analysis in order to determine the quantity of emitting material as a function of temperature. This can then be used to help calculate the thermal bremsstrahlung microwave emission, which can then be compared with the observed microwave emission. Although a detailed, careful DEM analysis will only be done for the "characteristic" spectra described above, I will need such a curve for each location in the two-dimensional images. To achieve this, I will compare the quiet sun and active sun DEM curves, and seek appropriate scaling factors based upon convenient line intensity ratios so that an effective DEM curve can be obtained for each location on the maps. I have provided Dr. Monsignori Fossi with several SERTS spectra, and she is currently in the process of using those spectra to derive characteristic DEM curves. After she has completed her analysis, I will use the curves to help calculate the thermal bremsstrahlung microwave emission as briefly outlined above, and proceed as originally described in my proposal.

During the next several months I plan to submit for publication a paper containing lists (providing wavelength, identification, intensity, measurement uncertainties, etc.) of the emission lines found in each of the SERTS characteristic spectra. This paper will describe some of the plasma diagnostic capabilities of these spectra. It will provide information of value for CDS/SoHO, namely, line lists which can be used to assess the validity of certain atomic physics parameters, and evaluations of plasma diagnostic techniques and/or DEM analyses.

TABLE 1

SERTS 1993 Active Region Average Line Intensity Ratios

Lambda (top)	Lambda (bot)	Intensity Ratio	Sigma (I ratio)	Log n_e or constant
Fe XVI				
360.787	335.424	0.499479	0.0807328	constant=0.482
Fe XV				
321.814	417.302	0.0546782	0.0173003	9.254 +0.229 -0.236
327.051	417.302	0.277134	0.0488723	constant~0.308
321.814	327.051	0.197299	0.0628598	9.271 +0.264 -0.259
Fe XIV				
353.855	334.194	0.441135	0.0705318	9.684 +0.147 -0.151
Fe XIII				
311.552	348.207	0.0150545	0.00720460	8.113 +0.130 -0.132
312.171	348.207	0.164142	0.0319168	off scale: too low
318.128	348.207	0.188664	0.0349205	9.157 +0.051 -0.051
320.810	348.207	0.458364	0.0755097	8.969 +0.130 -0.151
321.485	348.207	0.0900555	0.0196993	off scale: too low
359.674	348.207	0.928888	0.155803	9.188 +0.115 -0.090
359.854	348.207	0.220854	0.0408391	constant=0.293
312.171	359.674	0.176708	0.0349325	off scale: too low
318.128	359.674	0.203108	0.0382843	9.112 +0.126 -0.131
320.810	359.674	0.493455	0.0831707	7.617 +0.252 -0.259
321.485	359.674	0.0969498	0.0214869	off scale: too low
311.552	359.674	0.0162070	0.00777763	off scale: too low
359.854	359.674	0.237762	0.0447746	9.847 +0.119 -0.116
318.128	311.552	12.5321	6.09354	off scale: too high
320.810	311.552	30.4470	14.5797	constant=6.63
321.485	311.552	5.98198	2.99107	8.884 +0.191 -0.180
312.171	311.552	10.9032	5.34117	8.915 +0.173 -0.164
359.854	311.552	14.6703	7.13222	8.604 +0.283 -0.256
318.128	312.171	1.14939	0.244379	10.145 +0.207 -0.237
320.810	312.171	2.79248	0.544957	off scale: too high

321.485	312.171	0.548643	0.133034	constant=0.504
359.854	312.171	1.34550	0.285865	off scale: too high
318.128	359.854	0.854248	0.174211	9.243 +0.071 -0.072
320.810	359.854	2.07542	0.385313	9.206 +0.130 -0.171
321.485	359.854	0.407760	0.0957841	off scale: too low
318.128	320.810	0.411603	0.0764900	double: 7.880, 9.886
321.485	320.810	0.196472	0.0431006	>10
318.128	321.485	2.09498	0.492412	10.060 +0.221 -0.253

Fe XII

346.869	352.137	0.575773	0.0964762	constant=0.525
346.869	364.503	0.474572	0.0793112	constant=0.361
352.137	364.503	0.824235	0.134675	constant=0.687
338.296	346.869	0.860637	0.148839	10.039 +0.233 -0.269
338.296	352.137	0.495531	0.0839141	10.175 +0.229 -0.269
338.296	364.503	0.408434	0.0689879	10.198 +0.141 -0.131

Fe XI

308.549	352.708	0.0439535	0.0179981	off scale: too low
341.142	352.708	0.390829	0.0685218	constant~0.304
356.555	352.708	0.118703	0.0509405	constant~0.155
358.696	352.708	0.369270	0.0785718	constant~0.194
369.207	352.708	0.248437	0.0601556	constant=0.303
308.549	358.696	0.119028	0.0514557	off scale: too low
341.142	358.696	1.05838	0.236537	constant=1.57
356.555	358.696	0.321454	0.144965	constant=0.797
358.696	369.207	1.48637	0.414692	constant~0.641
308.549	369.207	0.176920	0.0791683	off scale: too low
341.142	369.207	1.57315	0.395808	constant~1.00
356.555	369.207	0.477801	0.222435	constant~0.511
308.549	341.142	0.112462	0.0466885	off scale: too low
356.555	341.142	0.303722	0.131983	constant=0.508
356.555	308.549	2.70066	1.54144	off scale: too high

Si IX

349.900	345.155	1.66630	0.295224	constant~1.5
341.991	345.155	0.367327	0.0721240	constant~0.43
344.974	345.155	0.144314	0.0412271	constant~0.25

Si VIII

319.855	316.223	1.67389	0.330873	constant=1.58

314.365	316.223	0.448463	0.109402	constant=0.52

Temperature Diagnostic Ratios (ionization stage in parentheses)

350.53(17)	335.42(16)	0.003866	0.001451	6.609 +0.038 -0.048
350.53(17)	327.05(15)	0.337136	0.127917	6.542 +0.038 -0.051
350.53(17)	417.30(15)	0.093432	0.035278	6.536 +0.038 -0.050
335.42(16)	327.05(15)	87.2148	14.9706	6.417 +0.019 -0.020
335.42(16)	417.30(15)	24.1702	4.04934	6.415 +0.020 -0.020
335.42(16)	334.19(14)	6.32560	1.01916	6.337 +0.036 -0.038
327.05(15)	334.19(14)	0.072529	0.012349	6.234 +0.038 -0.044
417.30(15)	334.19(14)	0.261711	0.043473	6.238 +0.032 -0.039
341.14(11)	345.75(10)	0.695793	0.124358	6.097 +0.023 -0.026

iron ion stage	log T_max
17	6.7
16	6.4
15	6.3
14	6.3
13	6.2
12	6.1
11	6.1
10	6.0

TABLE 2

SERTS 1993 Quiet Sun Average Line Intensity Ratios

Lambda (top)	Lambda (bot)	Intensity Ratio	Sigma (I ratio)	Log n_e or constant
Fe XVI				
360.788	335.419	0.479332	0.0772578	constant=0.482
Fe XV				
327.043	417.295	0.505604	0.128685	constant~0.308
Fe XIV				
353.855	334.188	0.326019	0.0536188	9.435 +0.117 -0.120
Fe XIII				
311.582	348.197	0.0331502	0.00917619	8.425 +0.148 -0.155
312.172	348.197	0.106559	0.0218281	off scale: too low
318.139	348.197	0.0510516	0.0137237	8.496 +0.227 -0.234
320.809	348.197	0.252893	0.0413691	8.506 +0.099 -0.102
321.466	348.197	0.0953745	0.0192978	off scale: too low
359.660	348.197	0.591856	0.102645	9.217 +0.179 -0.204
359.863	348.197	0.248891	0.0426241	constant=0.293
312.172	359.660	0.180043	0.0387362	off scale: too low
318.139	359.660	0.0862567	0.0238719	off scale: too low
320.809	359.660	0.427289	0.0753383	7.411 +0.234 -0.239
321.466	359.660	0.161145	0.0342859	off scale: too low
311.582	359.660	0.0560106	0.0159360	7.232 +0.332 -0.343
359.863	359.660	0.420526	0.0771489	9.399 +0.182 -0.172
318.139	311.582	1.54001	0.540402	double: 8.695, 9.243
320.809	311.582	7.62871	2.12555	constant=6.63
321.466	311.582	2.87704	0.871763	9.335 +0.423 -0.385
312.172	311.582	3.21444	0.979396	9.956 +0.267 -0.254
359.863	311.582	7.50797	2.12624	8.888 +0.090 -0.087
318.139	312.172	0.479091	0.142505	9.423 +0.173 -0.182
320.809	312.172	2.37327	0.491968	>9.7
321.466	312.172	0.895037	0.213973	constant=0.504
359.863	312.172	2.33570	0.498446	off scale: too high

318.139	359.863	0.205116	0.0564885	8.646 +0.267 -0.278
320.809	359.863	1.01608	0.176982	8.614 +0.119 -0.124
321.466	359.863	0.383198	0.0808539	off scale: too low
318.139	320.809	0.201870	0.0546447	double: 8.862, 9.121
321.466	320.809	0.377133	0.0772440	9.511 +0.254 -0.240
318.139	321.466	0.535275	0.158296	9.152 +0.106 -0.109

Fe XII

346.874	352.131	0.462943	0.0763444	constant=0.525
346.874	364.501	0.391597	0.0650234	constant=0.361
352.131	364.501	0.845885	0.137750	constant=0.687
338.291	346.874	0.651983	0.116615	9.653 +0.225 -0.245
338.291	352.131	0.301831	0.0530909	9.490 +0.209 -0.225
338.291	364.501	0.255314	0.0451808	9.760 +0.233 -0.258
335.025	338.291	0.123955	0.0660806	off scale: too low
335.025	352.131	0.0374134	0.0197761	8.191 +0.351 -0.382

Fe XI

341.146	352.704	0.270969	0.0475401	constant~0.304
358.665	352.704	0.244070	0.0513584	constant~0.194
369.166	352.704	0.197698	0.0523327	constant=0.303
341.146	358.665	1.11021	0.240008	constant=1.57
341.146	369.166	1.37062	0.369121	constant~1.00
358.665	369.166	1.23456	0.362096	constant~0.641

Fe X

365.571	345.758	0.302806	0.0689081	constant=0.428

Si IX

349.893	345.151	1.61724	0.298636	constant~1.5
341.993	345.151	0.476410	0.106647	constant~0.43
344.982	345.151	0.242436	0.0464048	constant~0.25

Si VIII

319.848	316.229	1.75429	0.332833	constant=1.58
314.354	316.229	0.628980	0.130205	constant=0.52

Temperature Diagnostic Ratios (ionization stage in parentheses)

335.42(16)	327.04(15)	35.0119	8.13241	6.317 +0.026 -0.033

335.42(16)	417.30(15)	17.7022	3.37902	6.383 +0.017 -0.021
335.42(16)	334.19(14)	2.03338	0.325469	6.242 +0.020 -0.018
327.04(15)	334.19(14)	0.0580768	0.0134913	6.210 +0.047 -0.052
417.30(15)	334.19(14)	0.114866	0.0219294	6.148 +0.034 -0.030
341.15(11)	345.76(10)	0.547833	0.0967784	6.065 +0.021 -0.023

iron ion stage	log T_max
17	6.7
16	6.4
15	6.3
14	6.3
13	6.2
12	6.1
11	6.1
10	6.0

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

Spectra of solar active regions, quiet sun areas, and areas above the limb were obtained from NASA/GSFC's Solar EUV Rocket Telescope and Spectrograph (SERTS) observations of 7 May 1991 and 17 August 1993. IDL software was written to analyze the spectra and measure the emission line wavelengths, widths, integrated intensities, and corresponding associated uncertainties. Intensity ratios among the numerous lines in the spectrum indicate (1) the validity of the SERTS relative wavelength calibration, (2) that the density derived from density-sensitive line ratios can vary by orders of magnitude even among line ratios from only one stage of ionization of iron, (3) that structures of similar density are found in both active and quiet sun regions, and (4) that active regions are, not surprisingly, hotter than quiet regions. A collaboration was established with Dr. Brunella Monsignori Fossi, who will use her existing code to perform differential emission measure analyses on the derived spectra. These DEM curves will be used to expedite the numerical and theoretical calculations necessary to achieve the goals of the present project, namely, determine the three-dimensional structure of the coronal plasma and magnetic field. This project will enable the evaluation of atomic physics parameters, plasma diagnostic techniques, and DEM analyses, all of which provide valuable input for CDS on SoHO.

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